PROGRESS IN PHOTOVOLTAIC ENERGY CONVERSION

By

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ABSTRACT

Progress in the photovoltaic conversion of solar energy is reviewed starting with the observation of the photoelectric effect in selenium in 1877, through the revolutionary development of the diffused P-N junction silicon photovoltaic cell in 1953-54, to recent evolutionary improvements of photovoltaic arrays used to provide long-duration on-board electric power for modern space vehicles.

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1. BACKGROUND

A review of the literature (Refs. 1-6) reveals that prior to 1954 photovoltaic cells (photoelectric cells) were operating at efficiencies ranging from 1/10 to about 1 per cent, depending on the characteristics of the individual cell and the spectral distribution of the incident sunlight. Historically, the first cells were made from polycrystalline selenium and were developed primarily as measuring and actuating devices. From the early work of Adams and Day (Ref. 1), who reported in 1877 that they had observed a photoelectric effect in selenium, to the Weston HGS photronic cell commercially available in the early 1950's, selenium type barrier layer devices were the more common photoelectric cells. These cells were frequently unstable and often experienced rapid deteoriation when exposed directly to sunlight.

In a related development, Ehrenberg, et. al. (Ref. 7) in early 1951 described the electron voltaic effect. Later that same year, Ohmart (Ref. 8) reported on a method of producing an electric current from radioactivity. The next year, Linder and Christian (Ref. 9) described the use of radioactive material for the generation of high voltages. Rappaport and Linder (Ref. 10)

at the RCA Laboratories investigated radioactive charging effects
with a dielectric medium in an attempt to obtain efficient
direct conversion of nuclear energy to electrical energy.
Rappaport soon directed his efforts toward the electron voltaic
effect in P-N junctions and in January, 1954, described (Ref. 11)
results obtained in experiments with high energy beta electrons
from strontium 90 and related isotopes. The direct conversion
of nuclear energy to electricity using P-N junction devices was
achieved, but the efficiency was disappointingly low. Work on
the electron voltaic effect in silicon and germanium P-N junctions
was continued through 1956 (Refs. 12-17), and produced two impor-
tant by-products:

    (1) Recognition of the potential of the P-N junction
devices as radiation detectors; and

    (2) Initial data on the damaging effects of radiation
on solar cell performance.

While Rappaport, Linder, and Loferski at the RCA Laboratories
directed their investigations to the use of P-N junctions in
silicon and germanium in the conversion of nuclear energy, Chapin,
Fuller, and Pearson (Ref. 18) at the Bell Laboratories were
experimenting with the use of P-N junctions in silicon for the

photovoltaic conversion of solar energy. Early in 1953, Chapin began an investigation in which he made extensive use of P-N junction formation techniques previously developed by Fuller and Pearson. This work resulted in the invention of the silicon solar cell which was first demonstrated by the Bell Laboratories during the annual meeting of the National Academy of Science in Washington, D.C., in April, 1954. (The actual demonstration consisted of a group of silicon photovoltaic cells assembled to form the "Bell Solar Battery.") The silicon solar cell was a result of the same advanced research and technology that produced the transistor at Bell Laboratories.

Soon after the announcement of the Bell solar battery, several papers describing the photovoltaic effect (Refs. 19-24) appeared in the literature. Rothlein and Fowler (Ref. 19) described results with germanium photovoltaic cells. Cummerow (Ref. 20) and Rittner (Ref. 21) reported on the use of P-N junctions for solar energy conversion. Reynolds, et. al., (Refs. 22 and 23) described the photovoltaic effect in cadmium sulfide. Prince (Ref. 24) provided a theoretical explanation for the photovoltaic effect in silicon and reported on recent progress in solar energy conversion at the Bell Laboratories.

Engineers at the Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, soon became interested in the potential of the photovoltaic conversion of solar energy for special purpose terrestrial and rocket vehicle applications.

In July, 1955, President Eisenhower announced that the United States would launch an earth satellite as part of the International Geophysical Year (1957-58). The project to place a United States satellite in orbit about the earth was called "Vanguard" and was assigned to the Navy.

The Army Signal Corps worked to improve the silicon solar cell and continued to advocate its use as a power source for high altitude rocket payloads and earth satellites. Ziegler (Ref. 25) described the use of solar cells to power instrumentation for upper atmosphere rocket research before an audience at the University of Michigan in early 1956.

Signal Corps was able to persuade the Naval Research Laboratory to use silicon solar cells to power one of the transmitters on the small Vanguard test satellites. One of these, Vanguard I, was placed in orbit on March 17, 1958, and continued to transmit data over its solar powered transmitter for about six years.

But prior to Vanguard I, the Army Signal Corps and the Naval Research Laboratory cooperated in the test of several solar cell clusters bonded to the exterior surface of the nose cone flown on the Aerobee HI-40 to an altitude of 126-miles from White Sands Proving Ground on April 11, 1957. Ziegler (Ref. 30) in a paper given at the IGY Rocket and Satellite Conference, Washington, D.C., September 30 - October 5, 1957 described the use of solar power sources for satellite applications. Concurrent with efforts to improve the silicon solar cell and to establish its suitability as a space power source, other semiconductor materials (Refs. 26-28) were investigated both theoretically and experimentally in an attempt to obtain photovoltaic solar cells superior to silicon, and further improvements and design data on silicon solar cells were obtained through 1957, 1958, and 1959 (Refs. 29-31, 34-39, 41-43).

The concept of large area, polycrystalline film solar cells was first described in the literature in 1958-59 (Refs. 32, 33, and 40).

With this brief background as an introduction to the photovoltaic conversion of solar energy, it should be helpful to first examine the availability of solar energy throughout the solar system.

2. SOLAR ENERGY IN SPACE

The availability of solar energy in space is shown in Fig. 1. The zero air mass (space) solar irradiance has been computed from terrestrial and high-altitude rocket data (Ref.) to be approximately 130 watts/ft^2 at one astronomical unit (1 A.U.) distance from the sun. If an inverse square law dependence is assumed, the solar irradiance would be 13,000 watts/ft^2 at 0.1 A.U. and would decrease to 1.3 watts/ft^2 at 10 A.U.

The Mariner 2 spacecraft which completed a successful flyby of the planet Venus in December, 1962, used oriented panels of silicon solar cells as the electric power source. This flight verified that satisfactory operation of photovoltaic power sources could be obtained at values of solar irradiance up to 250 watts/ft^2 and cell temperatures of 125°C.

The highly successful Mariner 4 spacecraft that recently obtained over 21 close-range television photos of Mars was powered by 28,224 silicon solar cells. This spacecraft confirmed the satisfactory operation of photovoltaic power sources over the range of solar irradiance from 130 to 55 watts/ft^2 and for equilibrium cell temperatures from about 55°C to -10°C.

The NASA, as part of its research and technology program in solar power generation, is endeavoring to determine the feasibility of using the photovoltaic conversion of solar energy as a source of spacecraft electric power for flyby and orbiter missions of the planets Jupiter and Mercury. The density of the solar energy available at Jupiter is sufficiently low that nuclear power sources may be preferable providing the radiation background does not seriously limit the accuracy of important scientific experiments and that reliable operating life compatible with the long mission durations can be achieved. On the other hand, the high density of solar energy at Mercury, about 10 times that at 1 A.U., may necessitate improvements in the technology of high temperature solar cells, or the development of more effective methods for controlling maximum cell temperature.

For missions close in to the sun (< 0.2 A.U.) the availability of large amounts of solar energy provides an attractive incentive for the development of an energy conversion technology to better utilize such an abundant energy source. However, the complexity of the thermal control problem and the higher flux of energetic particle radiation from the sun, particularly during solar flare

activity, may severely limit the usefulness of photovoltaic

conversion for these missions.

3. ELEMENTS OF SILICON SOLAR CELL

The elements of a typical silicon solar cell are shown in Fig. 2. Thin, silicon wafers are cut from single crystal ingots. Typical dimensions are 1-cm x 2-cm and 2-cm x 2-cm, with the trend toward the larger area cells. The economics of cells with 3-cm x 3-cm and 2-cm x 4-cm dimensions are also being investigated. In recent years, cell thickness has been decreased from about 0.020-inch to 0.012-inch in commercial production. As part of NASA's technology program, several thousand solderless, 2-cm x 2-cm, silicon solar cells of 0.008-inch thickness have been manufactured. More recently, an interest in ultra lightweight, high power photovoltaic arrays has lead to consideration of single crystal silicon solar cells as thin as 0.003-inch.

Wolf (Ref. 100) has reported on preliminary analytical and experimental work relating cell thickness with conversion efficiency. Further work to determine the limiting efficiency as a function of cell thickness is necessary. Such data, when combined with reliable structural weights and manufacturing costs, should be adequate to determine the optimum cell thickness for minimum array weight consistant with realistic array area and cost.

Commercial N on P cells have top and bottom electrical contacts of evaporated titanium and silver. However, Mandelkorn (Ref. 118) has recently suggested the use of a cerium-silver contact with a silicon monoxide-magnesium flouride antireflection coating and a very shallow junction. Cells manufactured in this fashion are reported to have an improved spectral response at the short wavelengths with a resulting improvement in resistance to radiation damage.

Early P-N junction solar cells were fabricated by solid state diffusion of boron into N-type silicon. Typical junction depth from the light sensitive (top) surface was believed to be about 2 to 3 microns in the early cells. More shallow junctions were considered desirable to improve the cells response to energy in the 0.4 to 0.6 micron wavelength region where solar energy is more abundant. The mismatch between the spectral distribution of the sun's energy in space and the spectral response of typical present-day cells is shown in Fig. 3. As will be discussed in a later section, the fact that artificial light sources at best provide only an imperfect simulation of the spectral distribution of the sun's energy, has resulted in many inaccurate and ambiguous reports of unusually high conversion efficiencies appearing in the literature.

Shallow junctions, only ¼ to ½ micron below the top surface, improved the short wavelength response of the cell, but resulted in decreased efficiency due to the increased series resistance of the diffused region. The introduction in 1959-60 of narrow extensions (grids) to the ohmic contact on the light sensitive surface made it possible to obtain overall improved performance with shallow junctions.

Experiments by Mandelkorn, et. al. in 1959-60 (Refs. 47 and 60), revealed that cells manufactured by diffusion of phosphorus into P-type silicon (N on P solar cell) were more resistant to radiation damage than were the P on N cells being used in space at that time. Mandelkorn's results were not immediately accepted, but over the past five years have been verified and a fairly plausible theory has been developed to explain the difference (Refs. 76, 95, and 100).

4. GROWTH IN PHOTOVOLTAIC POWER SOURCE PERFORMANCE

The growth in electrical performance of silicon solar cells for the period 1959-64 is shown in Fig. 4. The current-voltage characteristics were obtained from AM1 sunlight measurements on assembled arrays by dividing the array voltage by the number of cells connected in series and the array current by the number of cells in electrical parallel. Thus, the data shown are mean, in-circuit, characteristics for P on N silicon cells for the respective periods indicated. Both improvements in cell performance and array assembly processes are responsible for the growth shown.

The performance of N on P silicon cells has followed a different pattern. Knowledge gained from several years of experience with P on N cells made it possible to convert to the manufacture of N on P cells without a significant or permanent step backwards in the efficiency available prior to radiation damage. This was important for applications where the spacecraft would not be exposed to a severe radiation environment, such as for lunar and planetary missions, since increasing array area to compensate for lower cell efficiency would have been undesirable.

The fact that several months were required to obtain N on P cells with comparable efficiency did delay industry conversion to the more radiation resistant cell. Other factors such as the need for silicon monoxide antireflection coatings on the cell and conversion from nickel (gold) plated to evaporated titanium-silver electrical contacts caused some delay.

A comparison of the current-voltage characteristics of typical 10%AMO (28°C) cells with P on N and N on P structures is shown in Fig. 5. For equal efficiency, the N on P construction typically results in a cell with a higher short circuit current and a lower open circuit voltage.

The results of efforts at the Jet Propulsion Laboratory to improve the watts/lb of the photovoltaic arrays used on Ranger and Mariner spacecraft are shown in Fig. 6. The Ranger spacecraft (in August 1961) was the first to employ a 3-axis attitude control system and oriented panel-type photovoltaic arrays. Improvements in unoriented arrays of the paddle-type construction have been reported by Cherry and Slifer (Ref. 117). Unoriented arrays are typically lower in watts/lb performance by a factor of 2½ to 3 and higher in cost by perhaps a factor of 3 than oriented arrays. However, this is more than offset at low power levels by the

weight and cost of active attitude control systems unless such systems are required for other reasons.

The performance growth indicated by dotted lines for 1968 and 1972 are goals of NASA's technology program in photovoltaic conversion. Such improvements appear worthwhile and realizable within the time periods indicated.

Even though the technology indicated through 1964 has essentially been verified, this is not to say that every photo-voltaic array launched in 1964 operated at such a performance level. First of all, a spacecraft launch in 1964 implies that a reasonably firm design probably existed by the end of 1962. Second, conservative designs will be used if possible.

Since the structure accounts for more than half the total array weight, variations in the degree of conservatism reflected in the structural design may result in significant differences in array performance. A review of the spacecraft launched in 1964 reveals that the performance of oriented photovoltaic arrays ranged between approximately 6 and 10 watts/lb.

The growth in power per unit area of photovoltaic array is shown in Fig. 7. The trend has been upward at a modest rate and

minor improvements are expected over the next several years. NASA will be looking for new ideas that might lead to more dramatic efficiency improvements, but in view of previous work with similar objectives supported by the Army and Air Force there appears to be little reason for optimism.

The effect of sun-spacecraft distance on array efficiency is shown in Fig. 8. The change in efficiency is primarily associated with a change in array temperature with a partially off-setting effect from changes in open circuit voltage with level of solar irradiance. Martin, et.al., (Ref. 85) and Cunningham, et.al., (Ref. 96) have reported on the effect of temperature on solar cells after exposure to a radiation environment. At least two solar cell manufacturers, Hoffman (Ref. 91) and Heliotek (Ref. 120), have prepared design handbooks describing the effect of temperature, solar irradiance and charged particle radiation on typical cells selected at random from ordinary production runs.

Such data are considered adequate for purposes of preliminary design providing a margin of 10 to 20 per cent is used in sizing the array area. For detailed design, data on representative samples of the actual cells to be used are recommended.

5. STANDARD SOLAR CELLS

The accurate determination of the space (AMO) electrical output of solar cells and solar cell arrays from measurements performed using terrestrial sunlight or solar simulators has been a particularly troublesome problem since the beginning of the space program. The problem exists primarily because of the mismatch between the spectral distribution of solar energy in space and that of terrestrial sunlight or solar simulators. The spectral distribution of sunlight at the earth's surface continually changes throughout the day and will differ from dat to day. The light sources and optics used in solar simulators are subject to degradation and change with time and afford an imperfect simulation of the solar spectrum at best.

To further complicate the problem, the spectral response of the solar cell is different from cell to cell depending on the diffusion depth of the junction and surface coating. Other factors such as cell temperature, thickness and minority carrier lifetime in the base region have important effects on cell spectral response. In particular, radiation damage critically affects the base minority carrier lifetime and long wavelength response of the cell.

A specialists conference (Ref. 43) to deal with the
problem of solar cell measurement standardization was held in
December, 1959. Subsequent to this meeting a special working
subcommittee of the AIEE Solid State Devices Committee met on
several occasions in the Los Angeles area and evolved a specifi-
cation to cover the characteristics of solar simulators that
should be used for solar cell measurements.

The problem of standards and solar simulators was discussed
again at a meeting of the Solar Working Group (Interagency
Advanced Power Group) in February, 1962 (Ref. 76). Zoutendyk
(Ref. 81) reported on an empirical method involving sunlight
measurements at Table Mountain, California, over a range of
optical air mass with extrapolation of solar cell short circuit
current to zero air mass (space) conditions. Zoutendyk (Refs. 82,
98, and 121) has also reported on a method for obtaining space
calibrated standard solar cells by use of high altitude balloon
flights. Brandhorst (Ref. 100) has described a method for deter-
mining the zero air mass short circuit current of standard solar
cells that is an extension of Zoutendyk's earlier method.
Brandhorst used high altitude airplane flights to extend the
range of air mass measurements to very near space conditions
thereby reducing extrapolation errors.

A standard solar cell whose short circuit current under zero air mass conditions is known can be used to adjust solar simulators to the desired equivalent space solar irradiance (140 mw/cm^2 at 1 A.U.). It is then possible to obtain accurate measurements of the space efficiency of solar cells having a spectral response similar to that of the standard cell. A family of standard cells with known spectral response is required if the cells to be measured differ from each other substantially in spectral response, as is the case for cells irradiated to different integrated flux levels for radiation damage studies.

Use of either airplane or balloon calibrated standard cells should provide an acceptable solution to the measurements problem illustrated in Fig. 9. Here, a pyrheliometer (thermopile) having approximately equal response at all wavelengths has been used to measure the amount of incident solar energy with the result that the zero air mass efficiency appears to vary with time. The use of a standard solar cell to measure the equivalent zero air mass irradiance results in an accurate and reproducible efficiency measurement at any time of day.

6. ELECTRICAL DESIGN

The type (AC or DC) and amount (watts) of power to be delivered to the spacecraft loads, as well as the voltage level and degree of regulation, are important factors in the design of the electrical power distribution and control circuits. The efficiency of this conversion, inversion, and regulation equipment will significantly affect the area required for the photovoltaic array. The number of solar cells to be electrically connected in series will depend on photovoltaic array temperature, operating environment, and the mechanization of the overall photovoltaic/battery/electronic power system. Typical system considerations have been described by Robinson, et.al., (Ref. 97), Smith (Ref. 113), Dawson, et.al., (Ref. 116), and Menetrey, et.al., (Ref. 122).

The power -vs- voltage characteristics typical of the Mariner-Mars photovoltaic array are shown in Fig. 10. The system mechanization was such that the array operating voltage was on the high voltage side of the maximum power point. Since the array was sized to have adequate power at Mars, operation occurs near open circuit voltage when the spacecraft is near

the earth. The decrease in array temperature shifts the curve toward higher voltages while the decrease in solar irradiance reduces the available power output.

Systems designed for use with rechargeable batteries are frequently mechanized to operate in Mode 1 as shown in Fig. 11. In this mode the photovoltaic array resembles a constant current source. For operation in Mode 3, the array has characteristics resembling a constant voltage source providing temperature is not changing rapidly. Under conditions where maximum array capacity can be used for battery recharging, operation in Mode 2 may be desirable. Photovoltaic array performance rating is usually based on the power available at the maximum power voltage under specified temperature and solar irradiance conditions. In practice, both array temperature and solar irradiance will change throughout the mission and array characteristics may change as the result of radiation damage. Thus, end of life, or worst case extremes for the power -vs- voltage and current -vs- voltage characteristics must be used in power system design. As a result, the mechanization may result in very poor utilization of the actual array capability over a substantial part of the mission.

Part of the NASA program in electrical systems technology is
aimed at methods for achieving better utilization of the energy
capability of the array.

7. EXPERIMENTAL PHOTOVOLTAIC CELLS

Three types of experimental photovoltaic cell assemblies are shown in Fig. 12. These units were developed and assembled under Air Force contracts. Performance measurements were obtained at the Jet Propulsion Laboratory's Table Mountain solar test facility prior to an Air Force flight test then planned for 1963.

The dendritic silicon assembly consists of twelve, large area cells. The hoped for results of this research would be the capability to manufacture large area cells with efficiencics equl to those obtained on small, commercial silicon cells and at a significantly reduced cost. The Air Force has recently started a photovoltaic array program with Hughes Aircraft that would use dendritic cells manufactured by the Westinghouse Electric Corp. This program should provide significant data on the performance capability and economics of arrays using these cells.

The gallium arsenide (GaAs) assembly consists of twenty 1-cm x 2-cm single crystal, diffused junction cells. Analytical work by Jenny, et.al., (Ref. 26) and Loferski (Ref. 27) in 1956 focused attention on GaAs as a semiconductor material with a more

optimum bangap than silicon. The theoretical conversion efficiency
for the GaAs solar cell is higher than for silicon. Experimental
work over the past several years, however, has not produced
GaAs cells with an efficiency comparable to silicon (at least
not at 28°C cell temperature). In addition, GaAs cells are
quite expensive to manufacture relative to silicon. On the other
hand, the GaAs cell, with minor shielding, appears to be more
resistant to damage by charged particle radiation tnan the N on
P silicon cell now in use. Providing suitable electrical contacts
could be developed, the GaAs cell would be able to operate at a
higher temperature than silicon.

The polycrystalline cadmium sulfide cell can be fabricated
as large area, relatively thin devices, but have questionable
performance stability and low efficiency. In concept, the poly-
crystalline film cell would make possible a low cost, lightweight
photovoltaic array for space use and could conceivably break
through the cost barrier in terms of terrestrial applications.

In other work, film cells of cadmium telluride (CdTe) have
been investigated by Goldstein (Ref. 32) and more recently by
Cusano (Ref. 92). Aldrich (Ref. 100) has reported that CdTe
cells of nine square inches area have been made with efficiencies

close to 4%. These are probably to be compared with the 14% efficiencies reported for silicon cells.

Perkins (Ref. 100) has described the photovoltaic properties of GaAs thin films and has reported sunlight conversion efficiencies of 3% on small area devices.

In practice, the film cells fabricated to date tend to be unstable, are not light in weight or low in cost and are very low in efficiency. Whether further work can improve on this situation remains to be determined.

8. CONCENTRATOR PHOTOVOLTAICS

The concept of using auxiliary or integral reflectors with photovoltaic arrays to improve on such performance parameters as watts/lb and cost has been described by Evans and Menetrey (Ref. 54), Spies (Ref. 79), Tallent (Ref. 80), Cherry (Ref. 103), and others. An approach for using auxiliary reflectors to increase the electrical output of an existing photovoltaic panel is shown in Fig. 13. Lightweight reflectors made of aluminized mylar stretched across aluminum frames are being attached to an early Ranger prototype panel for performance evaluation in sunlight at Table Mountain, California. This approach has one obvious disadvantage: that of stowing the reflectors for launch and subsequent deployment. Improvement in cell output is less than might be expected because of an increase in cell temperature. Another potentially serious problem is the questionable stability of the reflective surface during ground testing and exposure to the space environment.

Tallent (Ref. 80) has described an integral V-geometry design that could potentially reduce the number of cells required to provide a given output by a factor of two. Since the

reflectors are integral with the array, stowing and deployment are simplified and heat rejection is improved. An 18.7-ft^2 panel, similar in general appearance and size to the Mariner-Mars panels, was fabricated for the Jet Propulsion Laboratory by the Boeing Company using the V-ridge reflector design. The panel employed 3,604 silicon solar cells (1x2-cm type) and was able to produce 150 watts under space conditions of 135 milliwatts/cm^2 and 55°C. Panel weight was about 15-lbs resulting in a specific output of 10 watts/lb. The power per unit area was 8 watts/ft^2. The total area of a photovoltaic array utilizing such integral reflector concentrating structures would probably be 10 to 20% greater than for non-concentrating panels such as those used on the Mariner-Mars spacecraft.

Photovoltaic concepts that would utilize concentration ratios of 10, 20, and higher have been studied for both space and terrestrial applications. For the high concentration systems, special cells designed to have very low series resistance have been investigated and spectrally selective coatings that reflect only the useful solar energy have been considered. Heat transfer loops with liquid coolant and secondary radiators have been suggested for thermal control of the photovoltaic converter.

Perhaps the most significant disadvantage of concentrator photovoltaics is the resulting complexity which undoubtedly implies a decrease in reliability.

9. HIGH POWER PHOTOVOLTAIC ARRAYS

It was popular in the early years of the space program (1957-60) to relegate photovoltaic conversion to power levels of less than one kilowatt. Competent photovoltaic device specialists helped in the propagation of the myth. Many were shocked when the Air Force proposed to study the feasibility of a lightweight 4-kilowatt photovoltaic power system. This year, 1965, the NASA will study the feasibility of using a 5-kilowatt photovoltaic/battery power system on an Apollo research laboratory; will continue to study the feasibility of solar electric propulsion for unmanned planetary missions based on the prospect that photovoltaic arrays up to 50-kilowatts in size and with specific weights of 50 lbs/kw may be possible; and will study the economics of manufacturing photovoltaic cells in sufficient quantity to provide power in the megawatt range for possible use on a manned planetary transportation vehicle using electric propulsion.

The practical utilization of such high power photovoltaic arrays will require that problems involving compact packaging, deployment, and spacecraft dynamics be understood and accounted for in the overall vehicle design.

The mythical limit on photovoltaic array size has been debunked, undoubtedly to be replaced by more practical engineering limitations not yet adequately understood.

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Prior to his present position with NASA, Mr. Smith was Head, Spacecraft Power Sources Group, Jet Propulsion Laboratory, California Institute of Technology, where he was responsible for the photovoltaic arrays used to supply on-board electric power to the Mariner and recent Ranger series of spacecraft. Mr. Smith made major contributions to the design, fabrication, and qualification testing of the most advanced photovoltaic power source to be used in space: that which powered the Mariner 4 spacecraft to a highly successful fly-by of the planet Mars in July, 1965.

ABLE I: GROWTH IN SILICON SOLAR CELL PERFORMANCE (1959-64)

YEAR	P_{mp} (mw)	η_{mp} (PER CENT)	COMMENTS
1959	14.4	5.3	MEAN OF 100-CELLS CONNECTED IN SERIES ON TEST PANEL ASSEMBLED IN SUPPORT OF VEGA SOLAR CELL ARRAY DESIGN — VEGA SPACECRAFT CONCEPT USED ON RANGER PROJECT
1960	17.5	6.5	MEAN OF 8680 CELLS (62-SERIES, 140-PARALLEL) ON EARLY RANGER SOLAR CELL ARRAY
1962	20.2	7.5	MEAN OF 10,710 CELLS (102 SERIES, 105-PARALLEL) ON MARINER VENUS SOLAR CELL ARRAY
1964	22.8	8.5	MEAN OF 28,274 CELLS (84-SERIES, 336-PARALLEL) ON MARINER MARS SOLAR CELL ARRAY

CONDITIONS:

(1). SOLAR IRRADIANCE (H) = 135 mw/cm^2

(2) TEMPERATURE (T) = 55°C

(3) AIR MASS ZERO SPECTRAL DISTRIBUTION (AMO)

(4) EFFICIENCY BASED ON 2-cm^2 AREA FOR 1x2 cm CELL

(5) I-V CHARACTERISTICS (FIG. 4) FOR MEAN CELL DERIVED FROM ASSEMBLED ARRAY CHARACTERISTICS. SOLAR CELLS HAD BEEN BONDED TO SUBSTRATE WITH EPOXY OF SILICONE ADHESIVE, HAD BEEN ELECTRICALLY INTERCONNECTED INTO SERIES SHINGLES OR FLAT, PARALLEL MODULES by SOLDERING AND HAD BEEN COVERED WITH 6-MIL CORNING 0211 MICROSHEET GLASS USING TRANSPARENT EPOXY OR SILICONE ADHESIVE BONDING

FIGURES

Fig. 1 : Availability of Solar Energy in Space

Fig. 2 : Elements of Silicon Solar Cell

Fig. 3 : Comparison of Solar Spectral Irradiance With Response of Silicon Solar Cell

Fig. 4 : Growth in Silicon Solar Cell Performance (1959-64)

Fig. 5 : Typical Silicon Solar Cell Current -vs- Voltage Characteristics (as individual cells)

Fig. 6 : Growth in Power Per Unit Weight of Photovoltaic Array

Fig. 7 : Growth in Power Per Unit Area of Photovoltaic Array

Fig. 8 : Typical Photovoltaic Array Conversion Efficiency -vs- Sun-Spacecraft Distance

Fig. 9 : Relative Photovoltaic Conversion Efficiency -vs- Time of Day

Fig. 10: Mariner-Mars Solar Cell Array - Typical Power -vs- Voltage Characteristics

Fig. 11: Effect of Power System Design on Photovoltaic Array Performance

Fig. 12: Experimental Photovoltaic Cells

Fig. 13: Auxiliary Reflectors to Enhance Photovoltaic Array Power Output

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